TETHERED ROTORCRAFT AS A MEANS OF ELECTRICITY GENERATION AT HIGH ALTITUDE

by
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1. Introduction: Over the last two decades ground-based windmills and windfarms have become commonplace. Here wind energy is used as an alternative, non-polluting means of generating electricity. A typical ground-based facility at Esperance, WA has been described by Hartley(1).

Wind is an environmentally attractive, non-polluting alternative because of the absence of greenhouse gases and nuclear emissions. However, tower mounted windmills are severely limited in their output due to the diffuse nature of the earthian wind resource. The available power at most of these sites is rarely more than 0.2 kW/m^2. This can be compared to the direct solar resource when the power density is again low at 0.4 kW/m^2. As a result the abovementioned machines are not ideally suited to the production of electricity at the multi-megawatt scale. In addition, this diffuse wind resource is highly unreliable. This means that the annual capacity or generating factor of any wind system is far below that available from coal fired or similar facilities. At Esperance for instance, the generating factor is typically about 28%.

It is also important to note that in all these operations adjacent to the surface there is powerful ground turbulence and other fatigue effects which severely degrade the life expectancy of the ground-based facilities. The realities of these ground facilities are dramatically and extensively examined in the US literature(2). Energy authorities are remiss for not fully examining the benefits that can be obtained by operating wind turbines at an elevated altitude in the powerful winds aloft. Atkinson et al(3) and O'Doherty and Roberts(4) have extensively reported on the availability of the upper winds above Australia and US territories. At altitudes of between about two and eight kilometres the winds are vastly more powerful and persistent than winds near the surface. This is particularly relevant to all of southern Australia. Around latitudes 30° in both hemispheres the annual power density can be as high as about 20 kW/m^2. Therefore, this elevated resource is about 50 to 100 times more powerful than that available from the best near-ground sites. In these regions the upper wind resource is so abundant and uniform that siting is an irrelevant problem. It is also particularly abundant in North and South America, China, Japan and the Mediterranean.

2. A Description of the Rotorcraft System: The system proposed herein and elsewhere by Roberts and Blackler(5) is two, or more, conventional windmill rotors tethered at altitude to form an elementary rotorcraft platform. Rye(6), Ho(7) and Strudwicke(8) have all made extensive studies of this simple configuration which has been used for low altitude experiments over four different flying models. Therein a pair of conventional rotors are mounted in a framed fuselage. Vertical fins are also advantageous. These rotors do not employ cyclic pitch control as would be used in conventional helicopters. Simple collective pitch control is used. It is this fact that makes these rotors identical and no more complicated than conventional windmill rotors. This model craft is tethered to the earth's surface by one or more, preferably three, composite aluminium-kevlar cables. The cable's separation distance to length ratio is about the same as that used on multi-stringed kites, and this should avoid any clashing effects between the cables.

The side-by-side rotors operate in contra-rotation. They are inclined at an adjustable angle to the on-coming wind, so that the rotor disks make an angle of up to about 40° to the wind. A rotorcraft with twin rotors each about 3.7m in diameter, is shown in Figure 1. Here the wind blows from right to left and acts on the rotors to generate lift, gyroplane-style. Simultaneously the wind forces the rotors to rotate thereby generating electricity, windmill style. The electricity so produced is conducted down the tethers to a ground station for connection to the grid system or other purpose. It should be noted that the rotorcraft performs two functions simultaneously. Thereby generating electricity while simultaneously providing adequate lift to keep the total system aloft. Of course limitations as to air space will vary according to the operational site. Nevertheless, it is this dual function that makes this system an attractive alternative proposition.

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The rotorcraft can also function as an elementary, powered helicopter. If electrical power is supplied from the ground through the tethers to the generators, which can also act as motors, then the craft can ascend or descend, helicopter-style, from a small ground base. This helicopter function is extremely useful as it allows the craft to be landed during wind lulls or during storms in any weather conditions. These landed periods can be used for service and/or maintenance purposes. Later, when conditions are favourable for generation, the craft can ascend in a helicopter fashion. It has been shown (3), (4) that at the best locations landings would be necessary about one day in seven for about 30 hours, taken as a yearly average. Landing operations at all sites would be less frequent in winter than in summer.

3. Trimmed or Equilibrium Flight Conditions: The classical rotor theories developed by Glauret, Lock, Wheatley and Bailey have been refined into a highly workable form by Gessow and Myers(9) and others. This theory has been applied to the current rotorcraft. Figure 2 shows a typical equilibrium configuration in side-elevation. The craft is at an incidence of α_c to the on coming wind. The cables are assumed massless and each at an angle of β to the horizontal ground. Each cable, two side-by-side rear cables and one forward cable, is of length L_c.

The rotor's aerodynamic performance can be written in terms of four basic parameters(9), namely the inflow parameter, λ, the tip speed ratio, μ, the collective pitch, θ_0, and the blade's linear twist θ_1. We will consider the case of an untwisted blade for simplicity[••], that is $\theta_1 = 0$. The rotor's thrust, T, directed along the control axis can be expressed in dimensionless form (9) as

$$C_T = \frac{T}{\pi R^2 \rho \Omega^2 R^2} = \tfrac{1}{2}\sigma a\left[B^3\theta_0/3 + \tfrac{1}{2}B\mu^2\theta_0 + \tfrac{1}{2}\lambda B^2\right] \qquad (1)$$

when a, σ, B are the blade's lift curve slope, the rotor's solidity and the tip loss factor respectively.

The rotor's drag or H-force acts normal to the control axis and this can be written in dimensionless form after reference 9. From the force equations and the momentum equation (2)

$$\tan\alpha_c = \lambda/\mu + C_T/2\mu\left(\mu^2+\lambda^2\right)^{\frac{1}{2}} \qquad (2)$$

one can deduce the equilibrium value of β as

$$\beta = \tan^{-1}\left[\frac{\left(\frac{2T}{mg}\right)\cos\alpha_c - \left(\frac{2H}{mg}\right)\sin\alpha_c - 1}{\left(\frac{2T}{mg}\right)\sin\alpha_c + \left(\frac{2H}{mg}\right)\cos\alpha_c}\right] \qquad (3)$$

where m is the mass of the craft.

Finally, the conventional windmill power coefficient, C_p, can be calculated as a function of the craft incidence α_c. This power coefficient (not the same as that defined in helicopter terminology) is defined as

$$C_p = \frac{P}{\frac{1}{2}\rho\pi R^2 V^3} \qquad (4)$$

where V is the wind velocity and P the power output. A plot of C_p as a function of α_c, and other parameters, is shown in Figure 3 for a typical machine.

4. A Discussion of the Power Coefficient Chart: Figure 3 is an important summary of the dimensionless power output from the system. The inverted U-shaped curves are typical of a conventional windmill system. However, it should be noted that the abscissa is the craft's attitude, α_c. Each U-shaped curve is plotted for a constant tip speed ratio, μ, where this parameter is defined as

$$\mu = V\cos\alpha_c/\Omega R \qquad (5)$$

In addition, all points on the U-shaped curves have been constructed at a blade incidence limit of 13°. It is interesting to observe that all the curves fall below the single curve labelled ideal power coefficient. This curve can be calculated from first principles assuming zero profile drag on the blades. As a result this single, upper curve represents the ultimate or ideal power output

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[••] Zero twist angle is not an optimum choice for power production.

available. Any real system will always lie below this curve. It can be seen that as α_c approached 90° so the power coefficient approaches the well-known Betz limit of 16/27. Futhermore, C_p tends to zero as α_c approaches zero. Finally, when operating this machine it would be advantageous to work at or near the top of the U-shaped curves in order to extract the maximum power output.

5. Discussion of The Autorotation Conditions: In Figure 3 it is also useful to locate where each of the left hand branches of the U-shaped curves cut the abscissa. For example, $C_p = 0$ at $\alpha_c = 22.5°$ when $\mu = 0.1$. In otherwords, if the system was on the point of collapse, with no power being produced, then the so called autorotation conditions are located as described on the abscissa. These values, therefore, represent the minimum sustainable flight conditions without power being generated or supplied from the ground. In otherwords, when in this condition, the craft is ready for landing operations provided the wind forecast is for an extensive lull period.

6. A Brief Cost-Benefit Statement: In a recent study (which is continuing as a formal doctoral work) two altitudes of 15,000 and 30,000 feet have been examined in some detail. Here the cables were assumed to hang as catenaries with the wind loads on the cables thereby neglected. Twin, 35m diameter rotors were arbitrarily chosen for demonstration purposes•••. In all cases examined the cable's mass per unit of length was 0.23 kg/m. Half of this figure was allocated to the kevlar tensile member. The remainder was allocated to aluminium strands in the composite cables. An electrical transmission efficiency of 95% was also used. The resulting cables were around 10mm in diameter, thereby stressing the kevlar to an adequate and safe tensile stress.

It is possible to construct power output-duration curves using known wind probability charts (3), (4) at the altitudes in question. A summary of the major findings are given in Table 1. Therein may be seen the annual energy outputs of 13.3 GWh and 18.2 GWh for the two altitudes. The annual value of this energy is around 1½ and 2 million dollars respectively.

Note also that the annual energy output per unit area of rotor can be as high as 9500 kWh/m^2 at the corresponding capacity factors. This figure can be compared to the ground-based equivalent of only 750 kWh/m^2 at a capacity factor of 28% at the Esperance facility(1).

Finally, it seems that the major doctoral study(11) will forecast energy costs of around 4.7^c/kWh in optimal 10 to 15 MW units. These are highly attractive figures despite the complications of altitude.

7. The Stability of the Craft on Its Tethers: The lateral or positional stability of any machine on its tethers is most important. This has been extensively studied and solved by using a differential collective pitch control system in low altitude experiments. This stability aspect is crucial if the automated, pilotless rotorcraft is to be parked at altitude for long periods.

This control system has been developed by the author in association with Ho(7), Strudwicke(8) and Scott(12). It is currently giving outstanding results on a flying model. The differential collective pitch system is used to artificially stabilise the craft against a coupled roll-lateral transtational instability. This instability only occurs below a certain critical wind speed.

After some algebraic work it can be shown that equation (6) describes the perturbation dynamics of the system

$$M\begin{bmatrix}\ddot{y}\\ \ddot{\phi}\end{bmatrix} + D\begin{bmatrix}\dot{y}\\ \dot{\phi}\end{bmatrix} + K\begin{bmatrix}y\\ \phi\end{bmatrix} = \begin{bmatrix}\alpha\\ \beta\end{bmatrix}\theta_0 \qquad (6)$$

where θ_0 is defined as the differential collective pitch action. The references (7) and (8) can be consulted for full details, particularly page 49 of reference (7). The differential pitch control has been shown both theoretically and experimentally, to be particularly effective.

Finally, this absence of any cyclic pitch control mechanism will greatly enhance the cost and maintenance benefits that can be obtained from this tethered wind generator.

8. References:

1. Hartley, J.A. "Esperance 360kW Wind Farm", Nat. Energy Research and Development Program, Aust., NERDDP/EG/913, June, 1989, pp 1-43.

••• This 35m diameter has been chosen on the basis of a series of highly successful, large USSR helicopters. See for instance the development of the Mi-6, Mi-10, Mi-12 and Mi-26 range of rotors since 1957(10).

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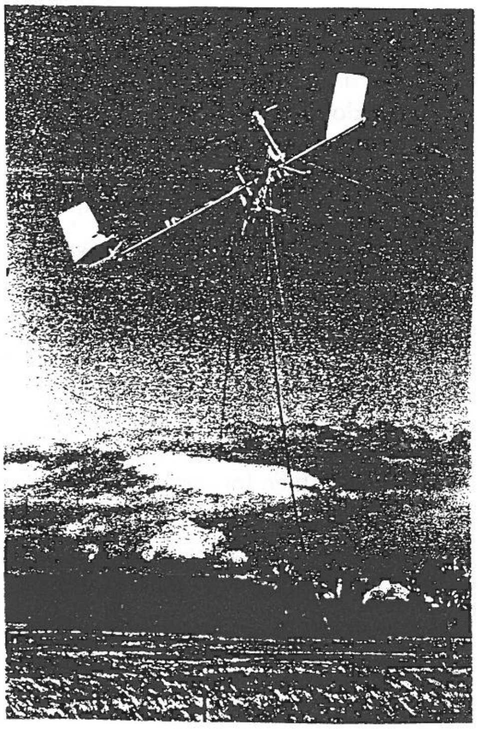

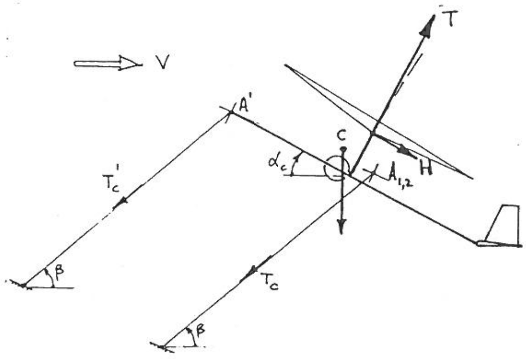

FIGURE 2 — ARRANGEMENT OF SYSTEM

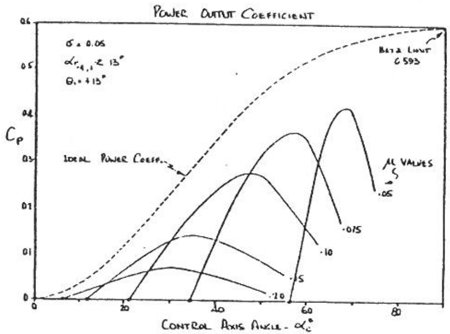

FIGURE 3

TABLE 1 Basic electrical parameters	Altitude, ft	
	15, 000	30, 000
Peak power output (MW)	3.13	3.13
Annual capacity factor(%)	48	67
Annual energy output (GWh)	13.3	18.2
Approx. value of energy ($/annum)	$1.5x10^6$	$2.0x10^6$
Annual energy output per m2 of rotor area (kWh/m2)	6910	9480
Annual landed time (h)	1780	1470
Percentage of time landed (%)	20.3	16.7